Antiproton Collection

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Run IIB AAC Review
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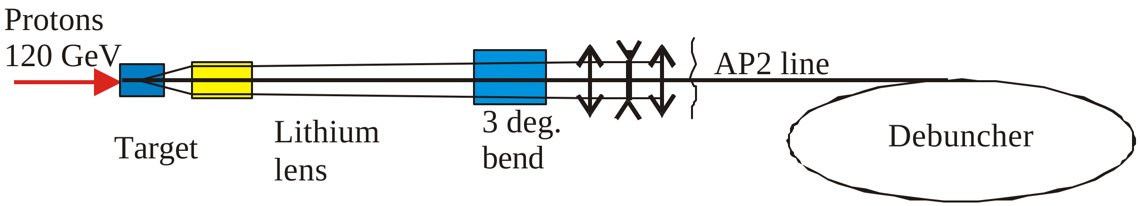
FNAL

Talk Outline

1) Introduction
2) Antiproton yield from nickel target
3) Lithium lens and optimization of its focusing
4) Antiproton transport from the target to Debuncher (AP2 line)
5) Current status and expected improvements

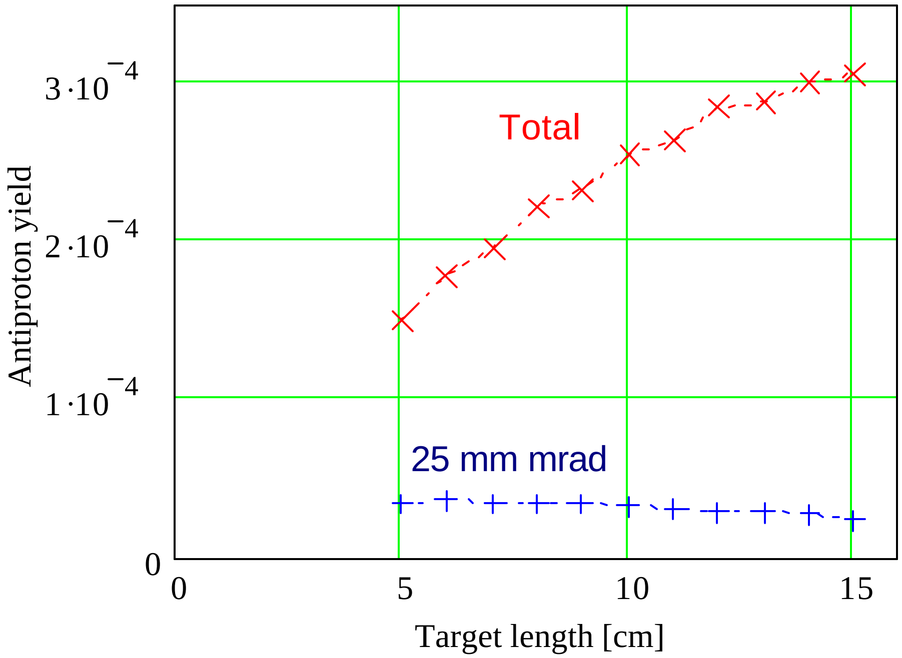
1. Introduction

- **Aim of the project**
  - Achieve maximum possible yield (number of antiprotons per proton)



    - We expect that we can improve it from **~14×10^{-6}** to **~40×10^{-6}**
- **Scope**
  - Physics of antiproton production, collection and transport
    - Optimization of antiproton capture
      - Target length
      - Beta function on the target
    - Scattering and absorption of antiprotons in the lithium lens
    - Effect of lens non-linearities
    - Chromatic effects in the transport line
    - Proton beam intensity limitations
  - Technical limitations
    - Lithium Lens Upgrade – Morgan
    - AP2 & Debuncher Aperture – Gollwitzer

2. Antiproton Yield from Nickel Target

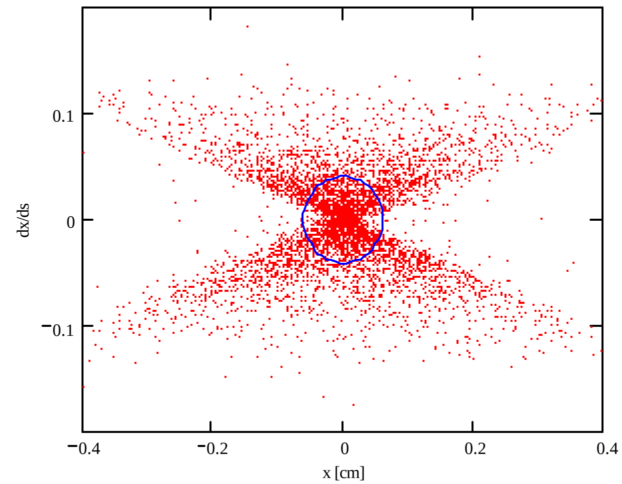


Total antiproton yield and optimized yield into 25 mm mrad as function of target length;

E_p =120 GeV

$E_{\overline{P}}$ =8 GeV

$\Delta p/p=\pm 2.25\%$

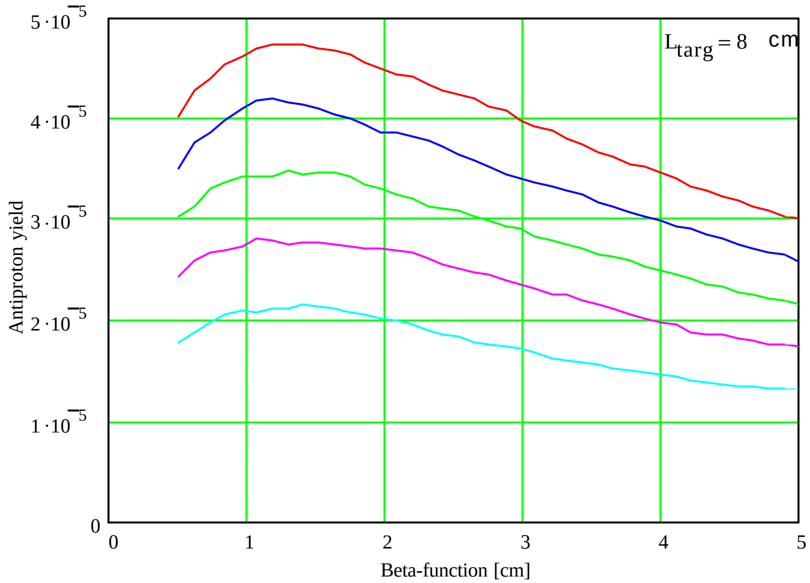


Phase space referenced to the beam waist (target center)

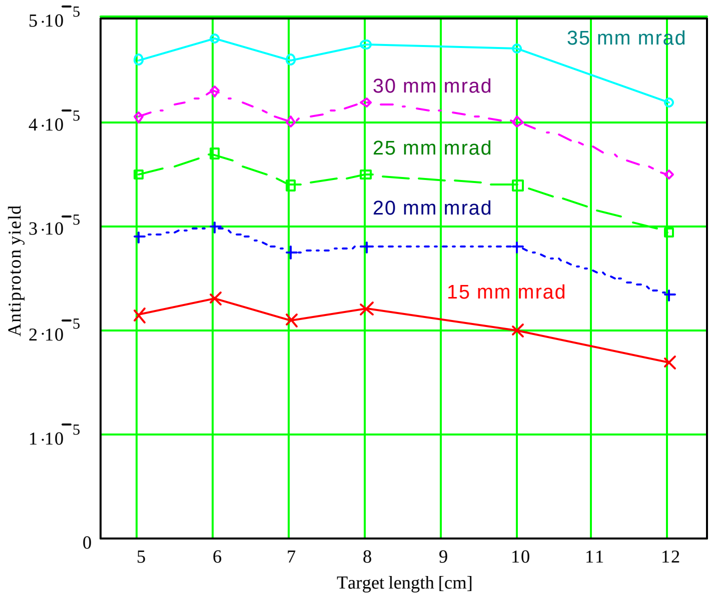
$$\left(\frac{x_i^2}{b^*}+x_i'^2 b^*\right)+\left(\frac{y_i^2}{b^*}+y_i'^2 b^*\right)\le e$$

$$\left|\frac{\Delta p_i}{p_0}\right|\le 0.0225$$

Antiproton production in the target has been simulated P. Bussey with MARS code (N. Mokhov)



Antiproton yield as function of the beta-function

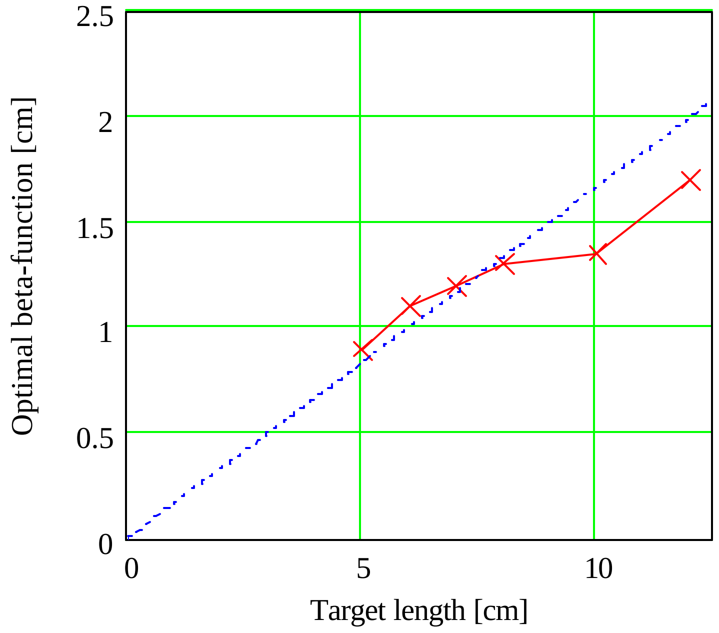


Antiproton yield as function of the target length for optimum beta-function

$\Delta p/p = \pm 2.25\%$

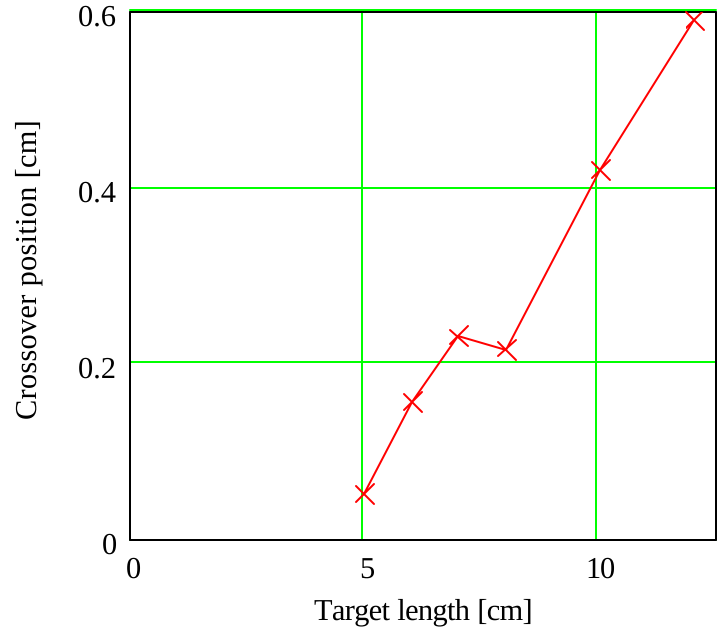
Beam acceptances of 15, 20, 25, 30 and 35 mm mrad

Rms beam size at the target is 100 μm



Optimum beta-function at the target center as function of the target length

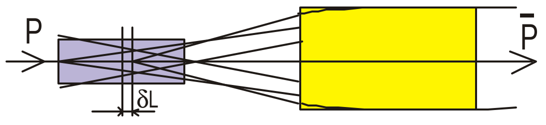
$$b^*_{opt} \approx L_{t\arg}/6$$

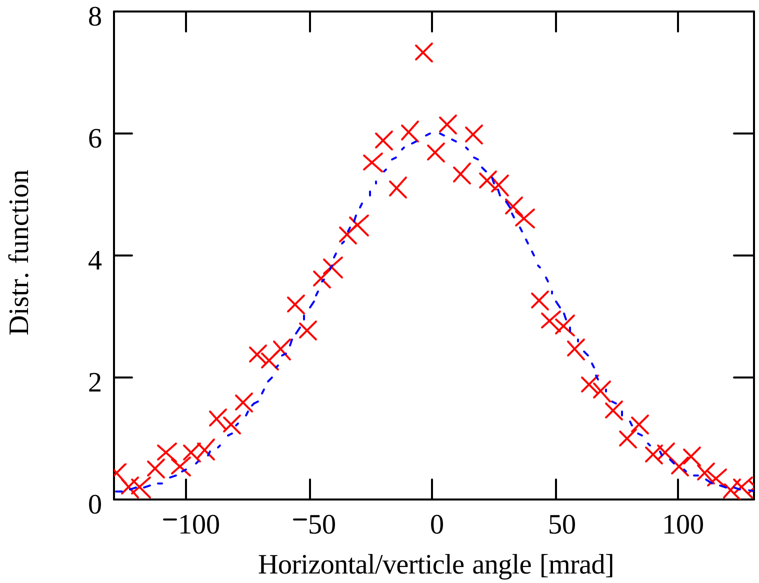


Crossover position as function of the target length

⇑

Scattering and absorption in the target lead to a shift of the beam waist downstream of the target center





Angular distribution function of 8 GeV antiprotons for 8 cm target

$$f(q) \propto \exp\left(-\frac{q^2}{2s_q^{\,2}}\right) \quad ,$$

$$s_q \approx \frac{1.1}{g}\sqrt{\frac{m_p}{m_p}} \quad ,$$

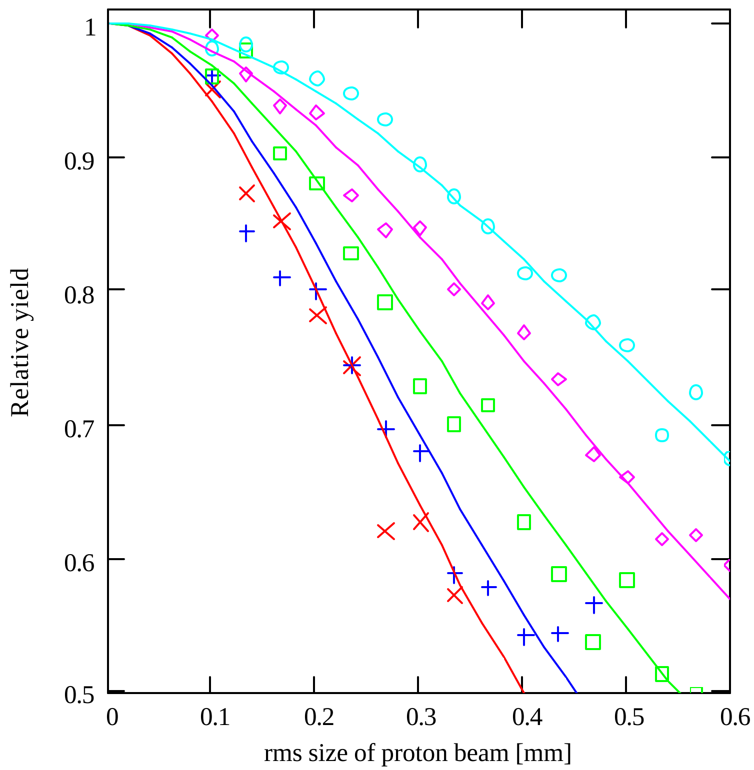
Effective emittance of outgoing antiprotons

$$e_{eff} \equiv b^*_{opt} s_q^{\,2} \approx \frac{1}{5}\frac{m_p}{m_p}\frac{L_{t\,\arg}}{g^2},$$

For 8 cm the target that yields

$$\boxed{e_{eff} \approx \ 26 \text{ mm mrad.}}$$

Dependence of antiproton yield on the proton beam size



Relative antiproton yield on rms size of the proton beam for acceptances of 10, 15, 20, 30 and 40 mm mrad (curves follow from bottom to top); target length of 8 cm, antiproton absorption and scattering in the lens are taken into account, lens gradient is 75 kG/cm.

- Energy deposition on the target limits decreasing the beam size
  - $E_D \approx 890[\mathrm{J/g}]\left(\dfrac{200\,\mu\mathrm{m}}{s_{pb}}\right)^2 \dfrac{N_p}{5\cdot 10^{12}}$
  - It is doubled due to particle shower
  - Presently, E_D~1000 J/g, s_{pb}~180 μm.
- Beam sweeping is required for 10^{13} proton on the target (Slip stacking)

3. Lithium lens and optimization of its focusing

Scattering and absorption of antiprotons in the lithium lens

- Nuclear scattering and absorption of antiprotons in the lithium lens is the major mechanism for antiproton loss in the lens

$$k_{lens} = \exp\left(-\frac{L_{Li}}{L_{Abs_{Li}}} - \frac{L_{Be}}{L_{Abs_{Be}}} \right) \approx 0.82 \quad \text{- for 15 cm lens}$$

L_{Li} =15.5 cm and L_{Be}=1.2 cm are total lengths of lithium and beryllium

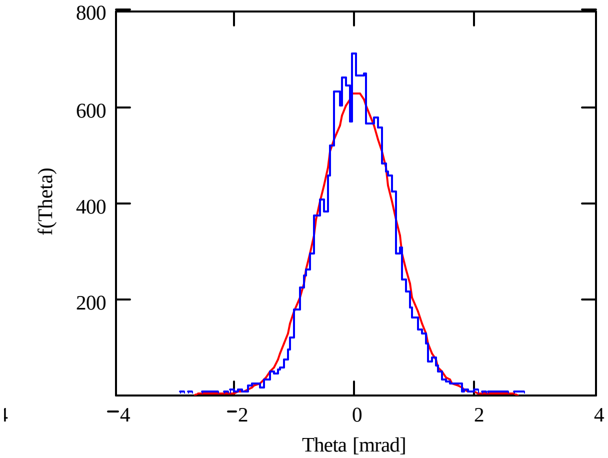
$L_{Abs_{Li}}$ =102 cm and $L_{Abs_{Be}}$ =30.2 cm are nuclear collision lengths for lithium and beryllium

- Multiple scattering in the lens can be estimated by the following formula,

$$\sqrt{\overline{q^2}} = \frac{13.6\ \text{MeV}}{ßPc}\sqrt{\frac{L_{Li}}{X_{Li}} + \frac{L_{Be}}{X_{Be}}}$$

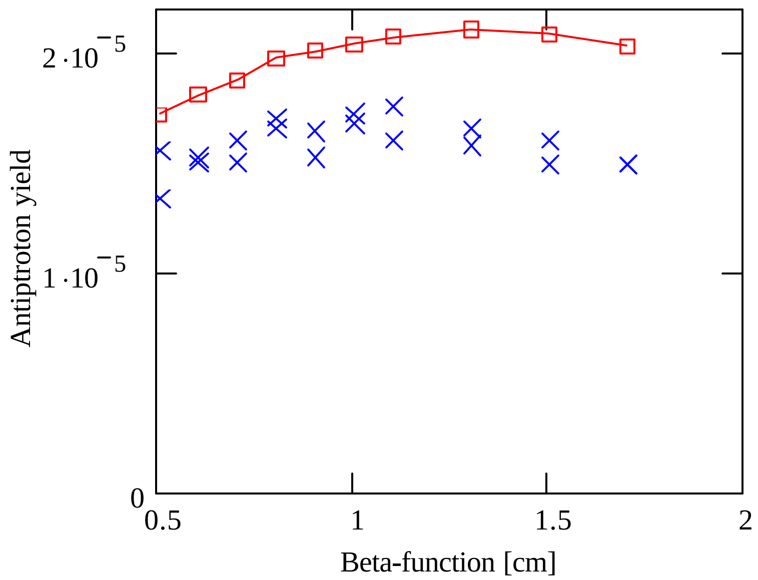
$$= 0.635\ \text{mrad} \quad ,$$

X_{Li}=155 cm and X_{Be}=35.3 cm are the radiation lengths for lithium and beryllium



Distribution functions of point like beam after passing through lithium lens simulated by MARS and computed with use of multiple scattering formula

Scattering in the lens changes optimum beta-function at the target



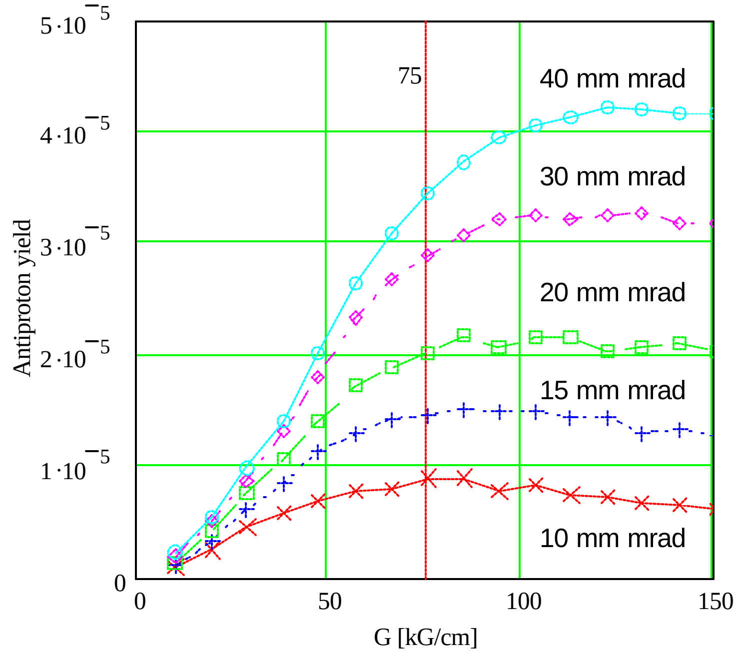
Antiproton yield on the beta-function at the target for acceptance of 15 mm mrad.

Solid line – no scattering and absorption in the lens,
× – only multiple scattering is taken into account.

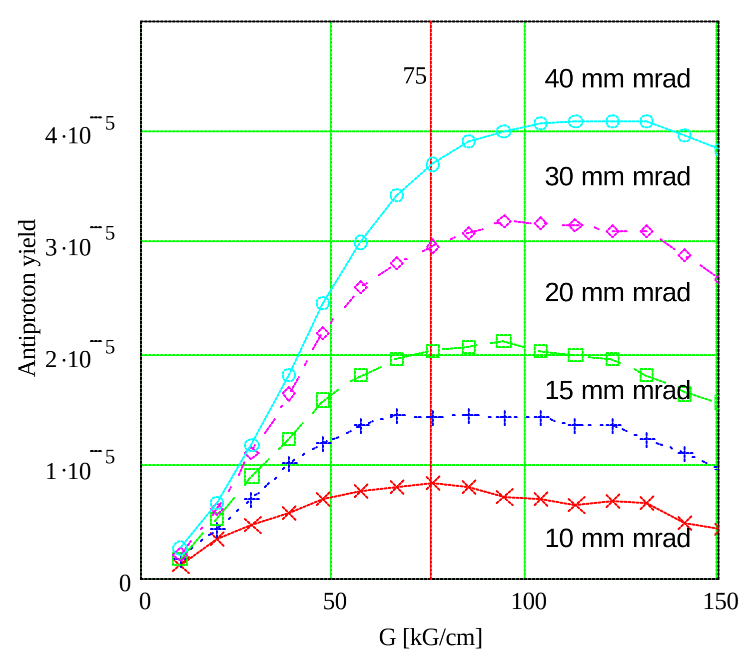
Emittance growth due to scattering

$$\Delta e \approx R_{lens}\sqrt{\overline{q^2}}$$

For the lens with radius of 1 cm that yields *De* = 6.3 mm mrad.



L_{lens}=15 cm



L_{lens}=18 cm

Antiproton yield on lithium lens gradient in the linear focusing approximation for lens lengths of 15 and 18 cm.

Rms proton beam size at the target is 130 μm. Energy acceptance is ±2.25%.

Present limitation of the lens gradient is 75 kG/cm

1 cm lens radius is well justified

- Focusing is $\propto \int B_{boundary} dl$, while design limits the pressure $P \propto B_{boundary}{}^2$

  $\Rightarrow$ Radius change does not change focusing
- Smaller lens radius is preferable for reducing of scattering effect
- Increased acceptance limits the minimum lens radius because of increasing beam size in the first triplet

Non-linearity of beam focusing in the lithium lens

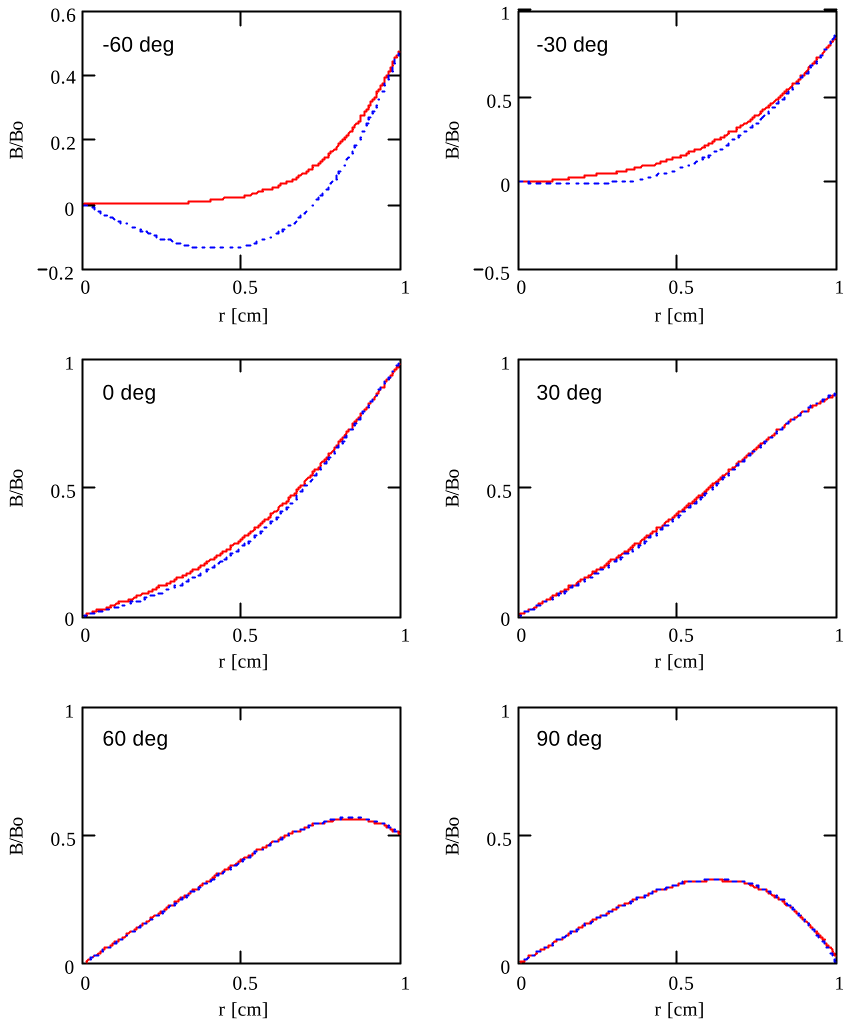
1. Skin-effect, $\Delta G/G \sim \pm 7\%$.

- 350 μs half period sinusoidal pulse
  - δ=0.5 cm versus 1 cm radius

Field calibration for 55 deg

$$B = \frac{2I_{lens}}{cR_{lens}} \cdot 0.948 \cdot 0.76$$

500 kA – 72 kG/cm



Dependence of magnetic field on radius

2. <u>Effect of temperature gradient on lens nonlinearity, $\Delta G/G \sim \pm 1\%$.</u>

Steady state solution

$$T(r) = T(0) + \frac{P}{4pk}\frac{r^2}{r_0^{\,2}} \quad \Rightarrow \quad \Delta T = 10\ \mathrm{K} \quad \Rightarrow \quad \Delta j/j = 4\%$$

$$B(r) = B_0 \frac{r}{r_0}\left(1 + \frac{1}{2}\frac{\Delta j}{j}\frac{r^2}{r_0^{\,2}}\right) \quad \Rightarrow \quad \Delta B/B = 2\%$$

Relaxation time = 1.2 s versus repetition time =1.5 s

Consideration of pulsed nature of lens heating exhibits significantly smaller result

3. <u>Effect of lens edges on lens nonlinearity $\Delta G/G \sim \pm 0.1\%$.</u>

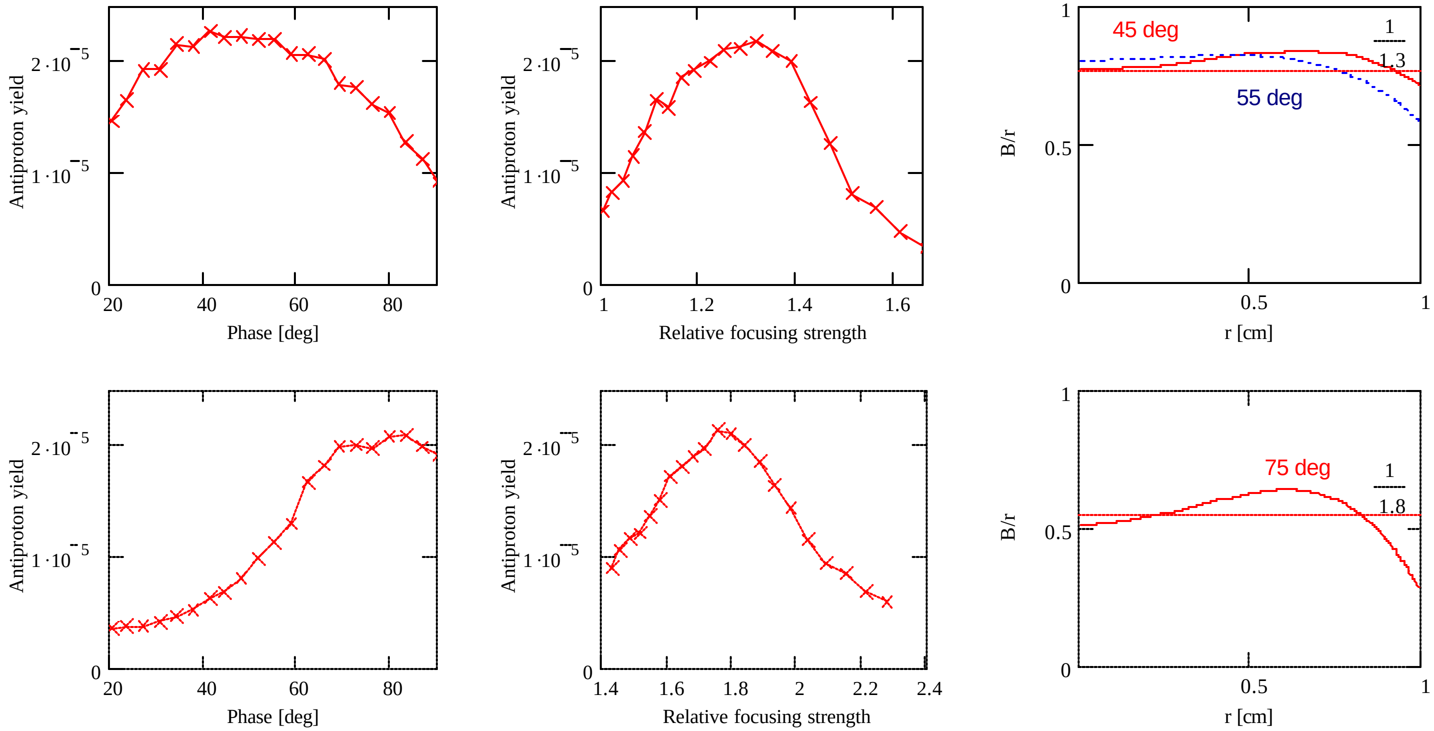
$$B_q(r,z) = \frac{2p}{c}\left[r j_z(z)\Big|_{r=0} - \frac{r^3}{8}\frac{d^2}{dz^2}\left(j_z(z)\Big|_{r=0}\right) + \frac{r^5}{192}\frac{d^4}{dz^4}\left(j_z(z)\Big|_{r=0}\right)\right] + \ldots$$

$$\frac{\Delta\Phi}{\Phi} = \frac{3}{8}\frac{rr'}{L_{lens}} \quad \Rightarrow \quad \Delta\Phi/\Phi \sim 10^{-3}$$

Dependence of antiproton yield on the pulse length of lithium lens current waveform

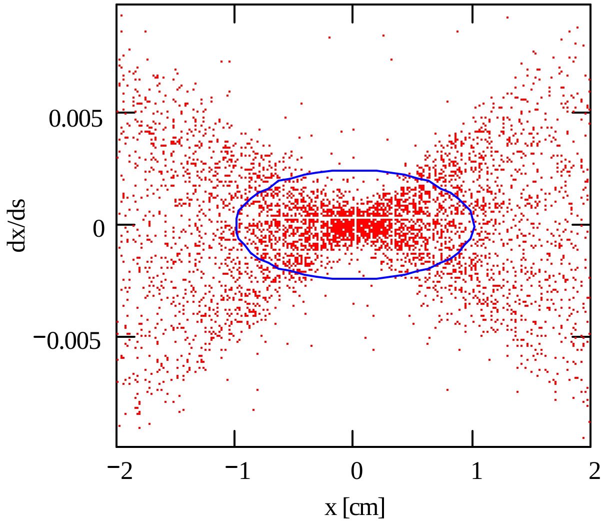
360 μs

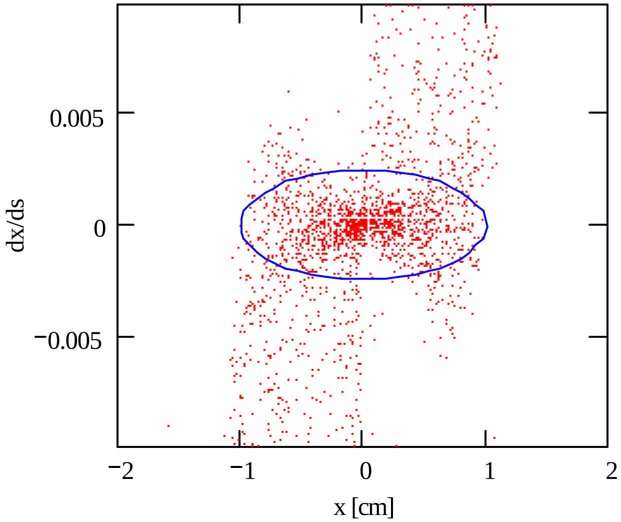
200 μs



- Lens pulse of 360 μs looks well optimized
    - o Longer or shorter pulse length will require more power deposition in the lens
- Non linearity does not cause significant particle loss

Effect of lens non-linearity and antiproton scattering on the antiproton yield





Antiproton yield

Ideal lens - $k = 3.25 \cdot 10^{-5}$

+Nuclear absorption - $k = 2.66 \cdot 10^{-5}$ (-18%)

+Multiple scattering - $k = 2.52 \cdot 10^{-5}$ (-6.5%)

+Lens nonlinearity - $k = 2.70 \cdot 10^{-5}$(+1.5%)

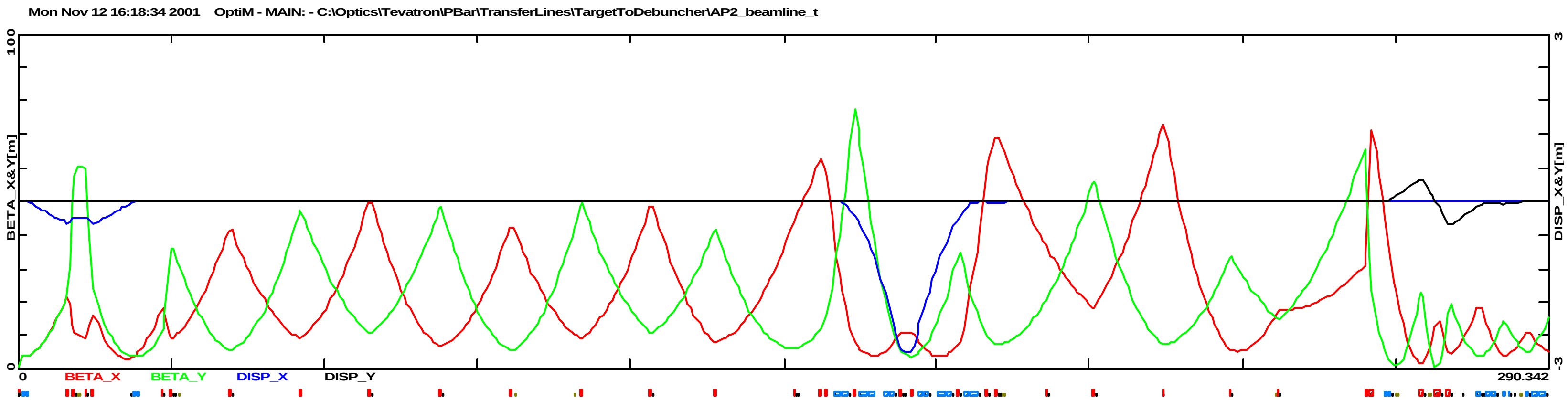
For

- Emittance 25 mm mrad
- Available accelerating gradient of the lens
- $b^* = 2.25$ cm
- $b_{lens} = 400$ cm
- lens to target length = 29.5 cm

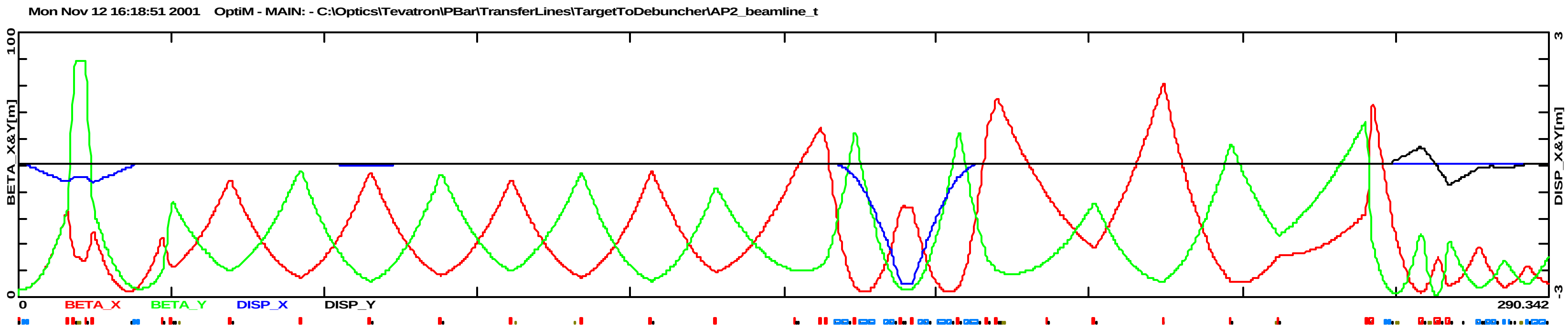
4. Antiproton transport from the target to the Debuncher (AP2 line)

Optics match in the line depends on acceptance

25 mm mrad



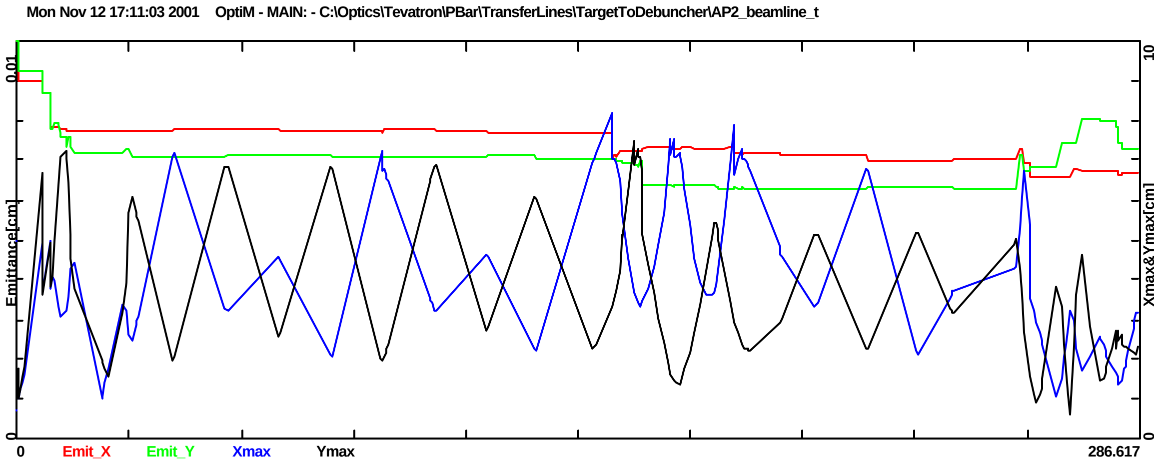
40 mm mrad



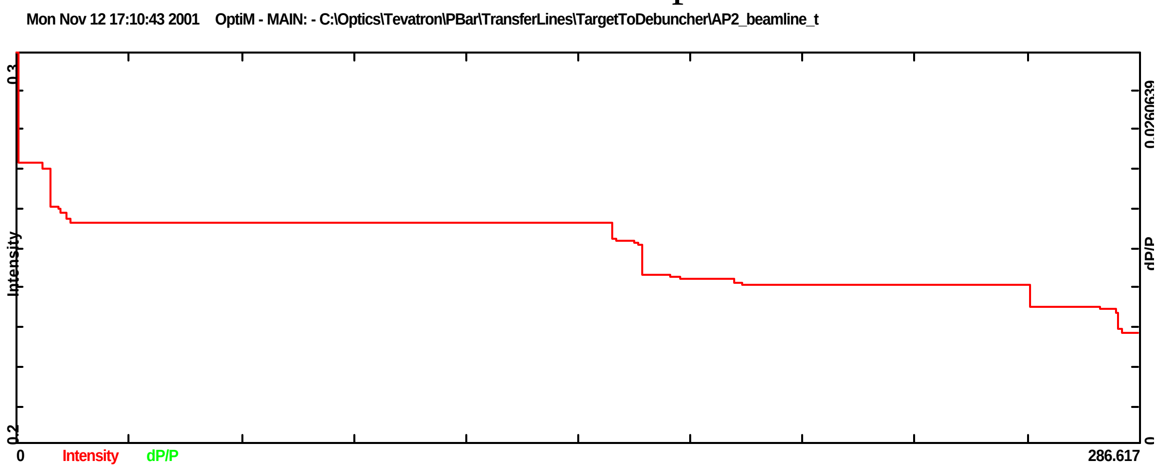
Tracking

– from the target to the debuncher with lens nonlinearity and scattering taken into account

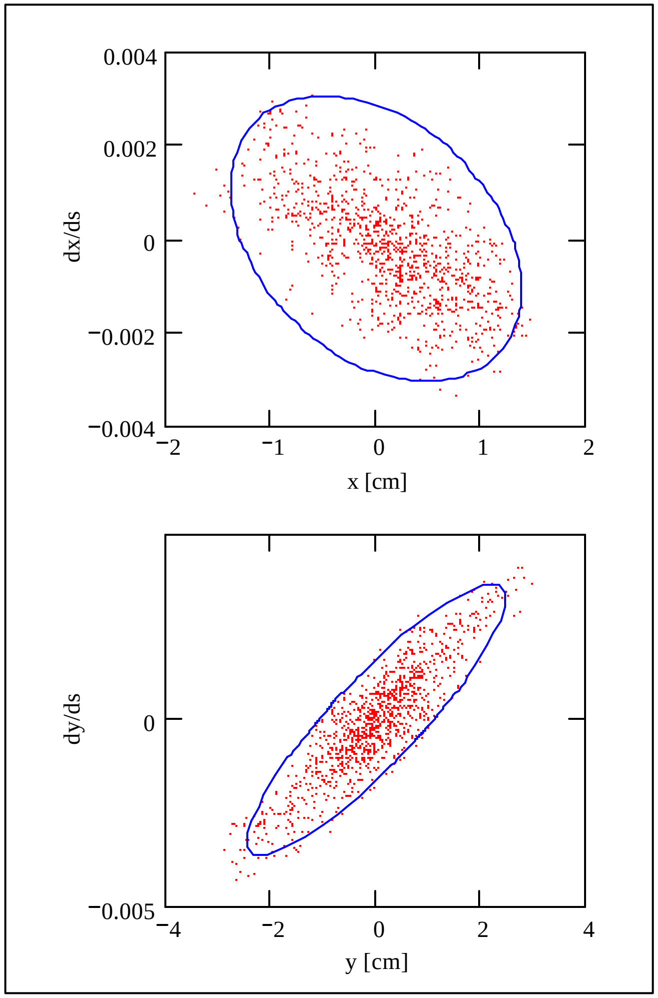
40 mm mrad acceptance



Beam emittances and beam envelopes

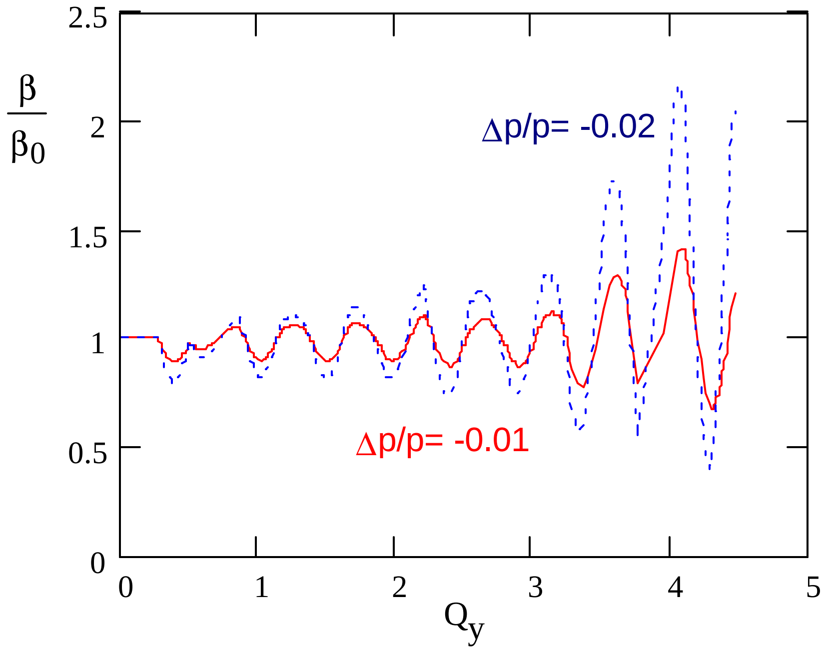


Beam intensity

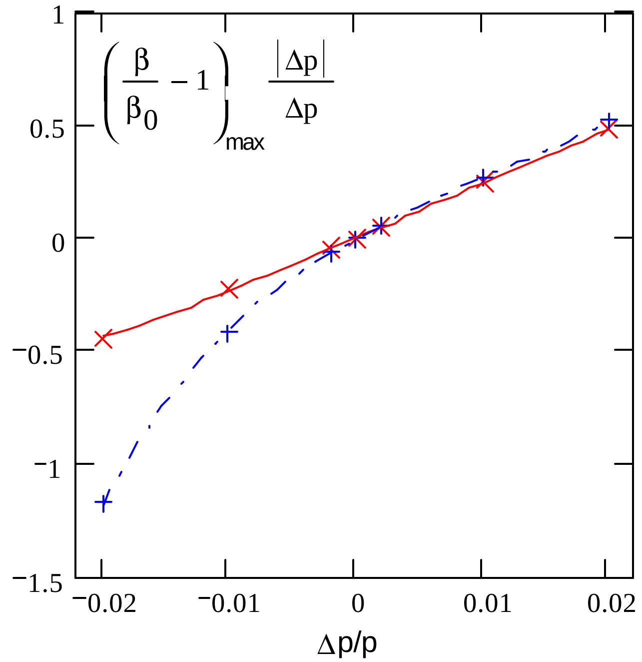


Chromaticity of beam envelopes

- Is responsible for ~10% emittance dilution at the end of the line

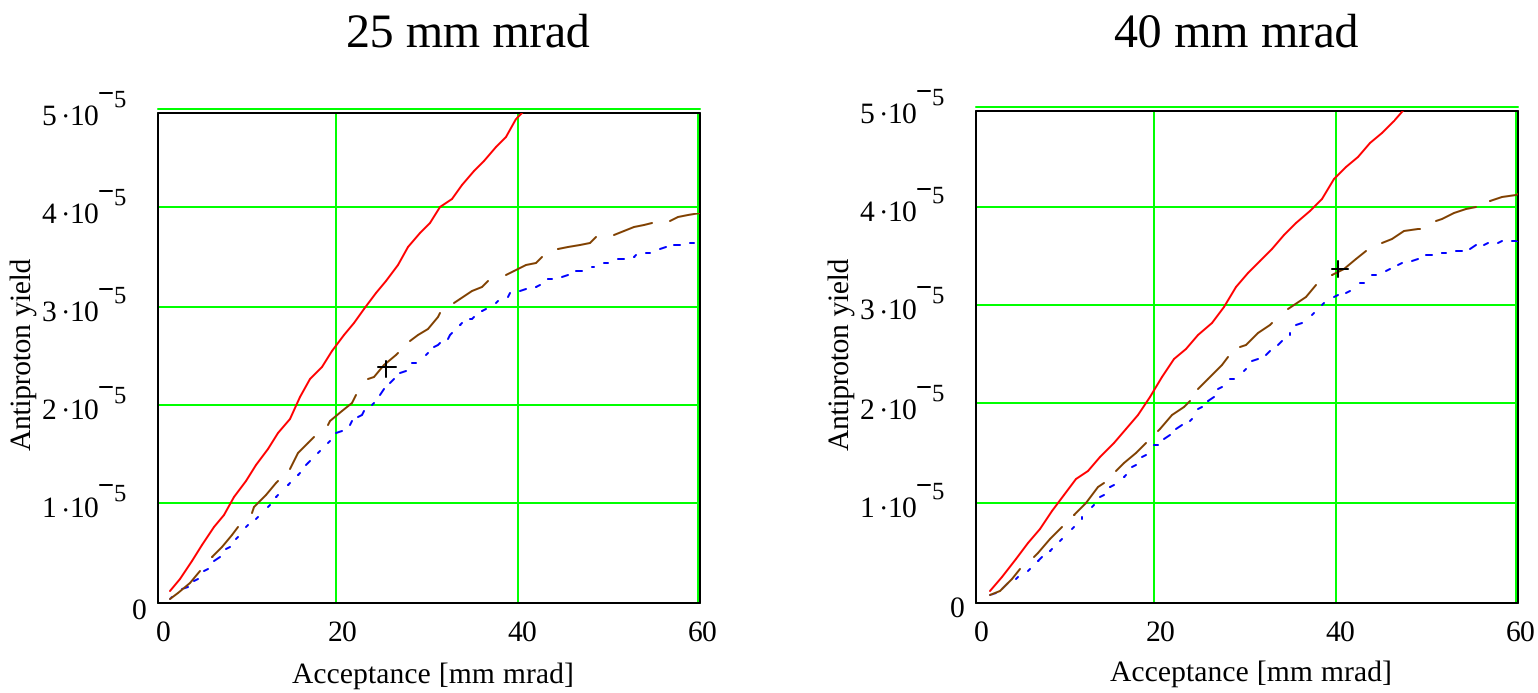


Relative variations of the vertical beta-function as function of the vertical betatron phase advance



Dependence of the maximum beta-function variation on momentum; solid curve – horizontal plane, dash-dotted curve – vertical plane

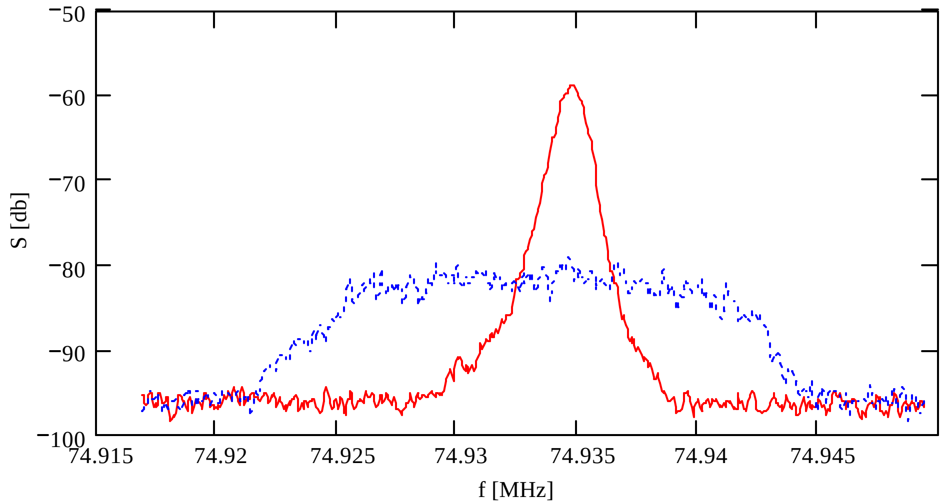
25 mm mrad　　　　　　40 mm mrad



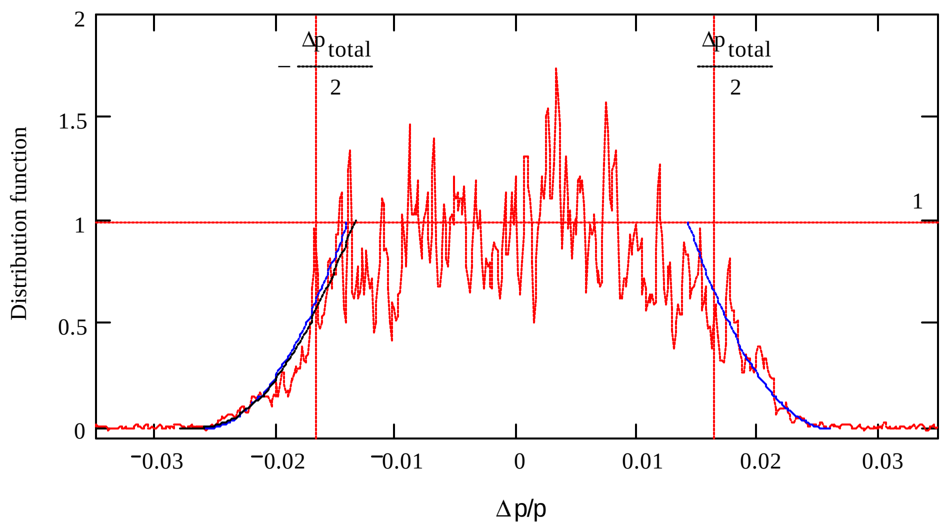
Dependence of antiproton yield on acceptance for optics solutions optimized for acceptances of 25 and 40 mm mrad, lens gradient 75 kG/cm;
solid curve – the yield at the target,
dashed curve – the yield in the center of the transport line (Q717),
dotted curve – the yield at the line end,
cross – the yield corresponding to the calculations

- Little dependence on the target beta-function yields little dependence on optics if there is sufficiently large aperture
- In reality steering errors cause stronger dependence on optics mismatches

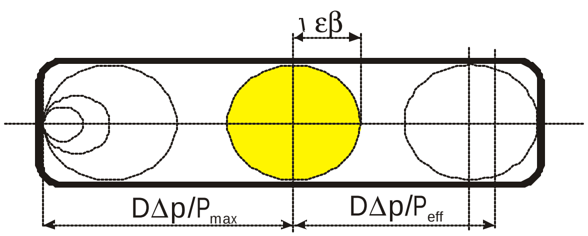
Debuncher aperture



Longitudinal Shottky spectrum



Longitudinal distribution function



$\Delta p/p_{max}=\pm 2.6\%$,

$\Delta p/p_{eff}=\pm 1.65\%$,

$$e_x \approx \frac{D^2 dp^2}{b_x}$$

If one believes in simple geometric scraping one obtains:

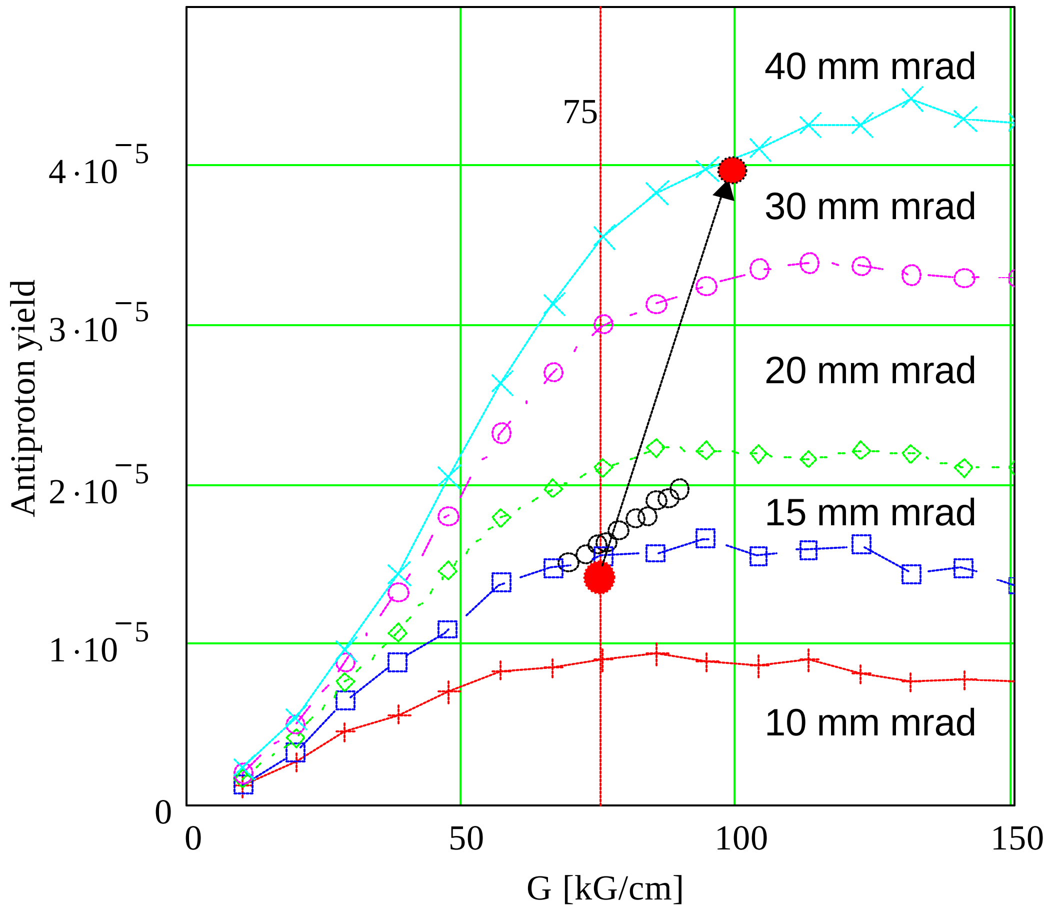
D = 2.08 m

β_ξ = 15.3 m

$\Rightarrow \; e_x \approx 40 \text{ mm} \cdot \text{mrad}$

It certainly is not right

5. Current status and expected improvements



Presently -

$$\frac{N_{\bar{p}}}{N_p} \approx (10-12) \cdot 10^{-6}$$

Run 1b best

(shown by ◌ on the plot)

$$\frac{N_{\bar{p}}}{N_p} \approx 17 \cdot 10^{-6}$$

Future

$$\frac{N_{\bar{p}}}{N_p} \approx 40 \cdot 10^{-6}$$

Expected gains

Improvement	Gain factor
Effective acceptance increase from 17 to 40 mm mrad with out compromising effective energy spread of ±2.2%	2.0
Increase of lithium lens gradient from 75 to 100 kG/cm	1.17
Optics correction at the end of AP2 line	1.1
Beam size decrease from 200 to 100 μm	1.04
Total	2.67

Total antiproton production is expected to grow from **~15×10^{-6} to ~40×10^{-6}.**

To get there we plan to:

1. Carry out careful study and correction of the transport line and debuncher optics and orbits
2. To open apertures in the debuncher and AP2 line
3. To improve parameters of the lithium lens
4. To install sweeping of the proton beam on the target
5. To rebuild the vertical dispersion suppressor with aim to reduce its chromaticity